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The potentiality of Sentinel-2 to assess the effect of fire events on Mediterranean mountain vegetation

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Abstract

Wildfires are currently one of the most important environmental problems, as they cause disturbance in ecosystems generating environmental, economic and social costs. The Sentinel-2 from Copernicus Program (Sentinel satellites) offers a great tool for post-fire monitoring. The main objective of this study is to evaluate the potential of Sentinel-2 in a peculiar mountainous landscape by measuring and identifying the burned areas and monitor the short-term response of the vegetation in different 'burn severity' classes. A Sentinel-2 dataset was created, and pre-processing operations were performed. Relativized Burn Ratio (RBR) was calculated to identify 'burn scar' and discriminate the 'burn severity' classes. A two-year monitoring was carried out with areas identified based on different severity classes, using Normalized Difference Vegetation Index (NDVI) to investigate the short-term vegetation dynamics of the burned habitats; habitats refer to Annex I of the European Directive 92/43/EEC. The study area is located in 'Campo Imperatore' within the Gran Sasso – Monti della Laga National Park (central Italy). The first important result was the identification and quantification of the area affected by fire. The RBR allowed us to identify even the less damaged habitats with high accuracy. The survey highlighted the importance of these Open-source tools for qualitative and quantitative evaluation of fires and the short-term assessment of vegetation recovery dynamics. The information gathered by this type of monitoring can be used by decision-makers both for emergency management and for possible environmental restoration of the burned areas.

Keywords

burn severity classes, NDVI, post-fire, satellite remote sensing, short-term vegetation monitoring

Introduction

Wildfires are currently one of the most important environmental problems as they cause disturbances in ecosystems generating environmental, economic and social costs (Viana-Soto et al. 2017). In recent years, Geographic Information System (GIS) techniques are more and more used for biodiversity conservation and human impact issues (Dominy and Duncan 2002; Foody 2008; Iannella et al. 2016, 2019a; D'Alessandro et al. 2018; Di Musciano et al. 2020), and revealed interesting results especially when coupled with ecological modelling (Santos et al. 2006; Iannella et al. 2018; Cerasoli et al. 2019; Iannella et al. 2019b; Lepcha et al. 2019) and remote sensing applications (Kerr and Ostrovsky 2003; Pettorelli et al. 2014, 2016; Wang and Gamon 2019).

Remote sensing has been used to monitor active fires and burned areas at the global and national scale (Giglio et al. 1999; Alonso-Canas and Chuvieco 2015; de Carvalho Júnior et al. 2015). Sensors like Advanced Very High-Resolution Radiometer (AVHRR), Moderate Resolution Imaging Spectroradiometer (MODIS), and Medium Resolution Imaging Spectrometer (MERIS) with spatial resolutions between 300 m and 1 km are generally used for these purposes (Mouillot et al. 2014).

Their daily revisit cycle is useful to capture active fire signatures or burn scars, however, the relatively coarse spatial resolution causes underestimations in case of burned area small extent. Comparisons between different burned area products generally show high variation in results (Padilla et al. 2015). A higher resolution of

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open source satellite image might strongly increase the estimation accuracy of burned area and the associated severity classes.

Satellite remote sensing (SRS) is ideal for monitoring burned areas, especially for large and remote places. Among the available satellites, the Copernicus Program (Sentinel satellites) offers a great tool for post-fire monitoring, both for the great spatial and temporal resolution, and for the accessibility of the data completely open source (Malenovský et al. 2012).

For burned areas detecting, optical satellite data from Multi Spectral Instrument (MSI) on Sentinel-2 (S2), starting from 2015, have a potential five-day temporal resolution (when the two satellites are operational) and have a spatial resolution of 10 m. S2 carries a multispectral sensor with 13 bands, from 0.443 to 2.190 μm. The visible RGB and the NIR bands are available at a 10 m spatial resolution, highly suitable for application in vegetation canopies. Four red-edge bands at 20 m spatial resolution are also available and are particularly suited for chlorophyll content analysis and to parametrize ecophysiological largescale models (Puletti et al. 2017). These features make S2 suitable for evaluating the unique fire events on the Apennines due to the relatively small extension of the burned areas or their configuration.

In the European context, the year 2017 was a record season for fires, especially in Italy for the amounts of hectares burned (Battipaglia et al. 2017; Frate et al. 2018). In summer 2017, the Abruzzo region (Italy) was strongly affected by fires, even of considerable size.

Fire is a frequent disturbance and a dominant factor in the evolution and ecology of Mediterranean areas (Schaffhauser et al. 2012; Tessler et al. 2015). For this reason, Mediterranean-type ecosystems are generally resilient to forest fire, mainly owing to the high proportion of plant species adapted to fires (Naveh et al. 1990). Post-fire plant species composition tends to revert to pre-fire composition through auto-succession or direct regeneration (Hanes 1971).

Nevertheless, these fires affected in some cases montane and subalpine regions where the plant communities are not adapted to this phenomenon, leading to net changes in the affected natural communities (Harvey et al. 2016). Moreover, montane species and ecosystems are also threatened by climate change (Brunetti et al. 2019). These communities are extremely important for the ecosystem services they provide and are characterized by a great heterogeneity of species showing different functional traits (Di Musciano et al. 2018).

In this paper we use the S2 satellite imagery, whose data can be freely downloaded from the Open Access Hub of the European Space Agency (ESA) for burned area monitoring purposes, as well as for searching approaches to study the effects of fire on vegetation (Verhegghen et al. 2016).

The aims of this study are i) to evaluate the potential of S2 to detect and quantify the burn scars and ii) to monitor the short-term vegetation dynamics in different 'burn severity' classes.

This approach was tested in the southern sector of the Gran Sasso massif (Abruzzo, central Italy) where wildfire events recently occurred. Moreover, to assess the short-term dynamics of vegetation recovery in the different habitat types (with reference to the Annex I of the European Directive 92/43/EEC; European Commission 2013) of montane and subalpine ecosystems, vegetation monitoring through S2 satellites was carried out. Furthermore, this study also investigated the response of Annex I habitat types to fire, a topic poorly present in the literature.

Materials and methods

Study areas

The study area is 'Fonte della Vetica' (Centroid coordinates: 42°24'56.44"N; 13°45'30.07"E), in the 'Campo Imperatore' upland plain falling within the Gran Sasso – Monti della Laga National Park in central Italy (Figure 1). The research focused on the habitats of the Annex I of the European "Habitats" Directive (92/43/EEC and subsequent amendments; http://vnr.unipg.it/habitat/).

The study area was chosen for the importance of its floristic (Conti and Bartolucci 2016) and vegetational (Biondi et al. 1999) biodiversity. Furthermore, the area falls within a Special Protection Area (SPA) (Birds Directive, 79/409/EEC and further updates) and in a Site of Community Interest (SCI) (Habitat Directive, 92/43/EEC). It is one of the largest upland plains in Italy, the largest in the Italian Apennines (Gratani et al. 1999), immediately next to the 'Corno Grande' peak, the highest in the Apennines (2912 m a.s.l.).

An accidental fire triggered by anthropogenic causes, which occurred between 5 and 9 August 2017, has devastated several important plant communities and left huge burned areas which represent the object of the present study.

Dataset and pre-processing

We analysed six images from S2 satellite (Spatial resolution: 10 m, Radiometric resolution: 12 bit) acquired by ESA's Open Access (https://scihub.copernicus.eu), with a time interval between July ÷ October 2017 and 2018, listed in the Appendix: Table A1.

In order to build the dataset, the aforementioned Level 1C (TOA – Top of Atmosphere reflectance) images were chosen based on the low cloud cover percentage and pre-processed for atmospheric correction (Szantoi and Strobl 2019) with the Sen2Cor (Louis et al. 2016) plugin (SNAP software – Sentinel-2 Toolbox) provided by ESA. Following the atmospheric correction, we obtained the Level 2A (BOA – Bottom of Atmosphere reflectance) that is more useful than TOA reflectance when trying to detect a process on the surface such as a fire event, because the atmospheric effects caused by the event itself are reduced (Zhuravleva et al. 2017). Subsequently, a water-cloud mask was created by calculating the Normalized Difference Water Index (NDWI)

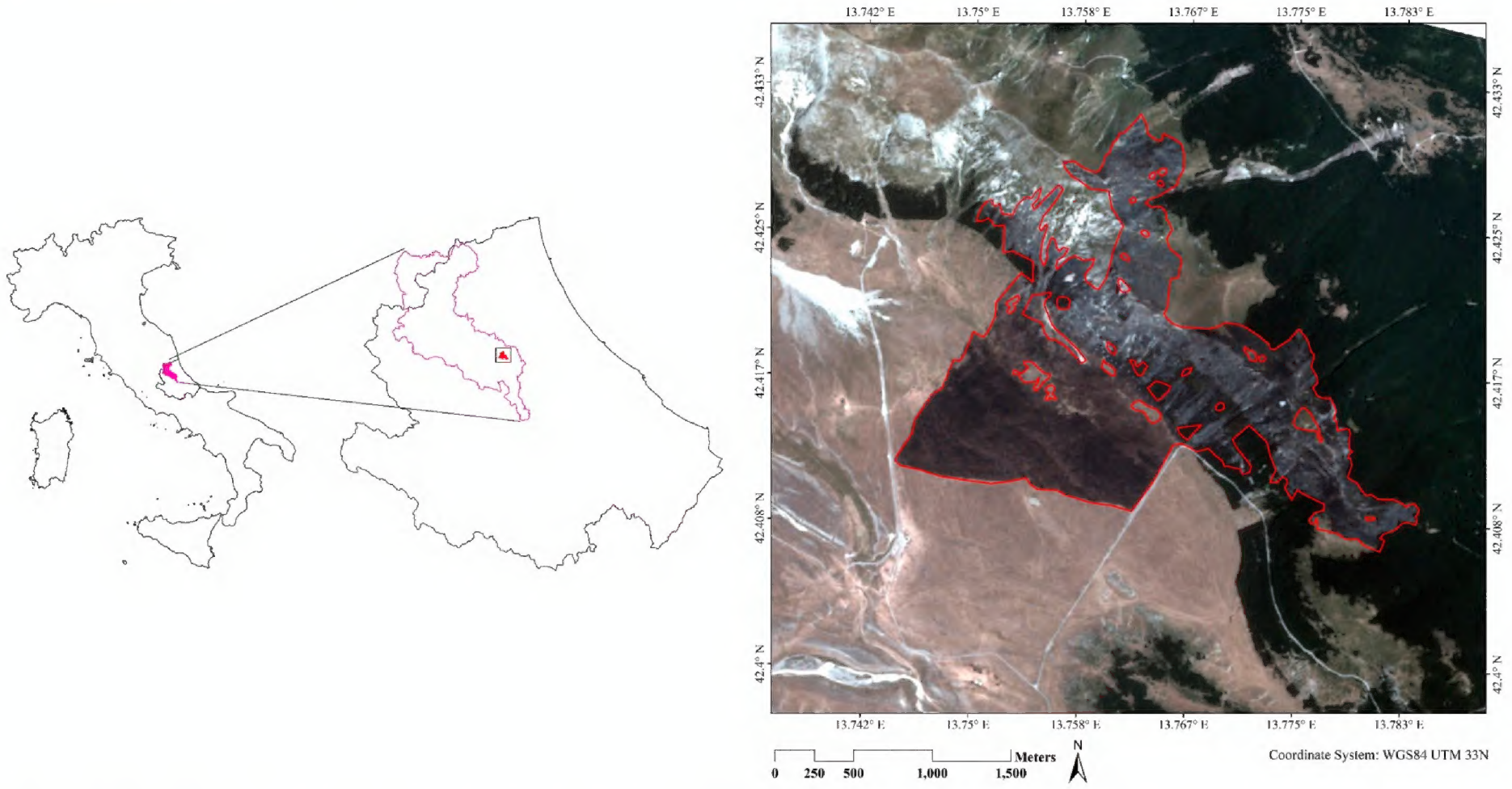

Figure 1. Map of the study area. Burned scar framed through Planet Scope image of 10 August 2017. Fire area perimeters are marked in red.

(McFeeters 1996) and applied to the multispectral indices (Relativized Burn Ratio – RBR and Normalized Difference Vegetation Index – NDVI) to correct possible biases caused by phenomena not directly related to fire's effects.

Detection of burned areas

The detection of burned areas was carried out by Relativized Burn Ratio index (RBR) (Parks et al. 2014), which allows the discrimination of the burned surface by severity classes (Moderate-Low, Moderate-High and High severity) on the basis of multitemporal raster (Spatial resolution: 10 m) of the pre- and post-fire situation, through a specific discrete class threshold proposed by the United States Geological Survey (Key and Benson 2006) (Figure 2).

The RBR was chosen because of its reliability in situations where the pre-combustion biomass is low or very variable and heterogeneous (Morgan et al. 2014).

The RBR is a relativized version of the Delta Normalized Burn Ratio (dNBR: NBRprefire – NBRpostfire) (Key and Benson 2006). Fire-affected areas have relatively low near-infrared reflectance (NIR) and high reflectance in the short-wave infrared band (SWIR). A high NBR value generally indicates healthy vegetation; on the contrary a low value indicates bare soil and recently burned areas (Prodan and Racetin 2019). To evaluate the accuracy of the RBR, considering that the index was assessed through ground field surveys and Visible Infrared Imaging Radiometer Suite (VIIRS, spatial resolution = 375 m) provided by the Fire Information for Resource Management System (FIRMS) (Davies et al. 2008), we further verified its accuracy by performing a random forest (RF) classification using the RStoolbox (Leutner et al. 2017) package in R environment. The 'superClass' function was used for the classification process, by keeping 80% of the data for training the model and the remaining 20% for validation; further, the Overall accuracy and Kappa statistics (Congalton and Green 2019) were obtained through the same function.

Vegetation monitoring

After the identification of the study area, rasters were manipulated in GIS (QGIS 3.4.5, QGIS Development Team 2016) and R (RStudio) (R Core Team 2016) environments to calculate the NDVI (Rouse 1974; Cherki and Gmira 2013; Addabbo et al. 2016; Viana-Soto et al. 2017). The NDVI is estimated as the normalized difference between the near infrared (NIR) and visible red (RED) bands, which discriminate vegetation from other surfaces based on the chlorophyll absorption of the green vegetation of the red light for the photosynthesis and reflection of NIR wavelengths (Tucker 1978). The index was calculated within three-time intervals: pre-fire, immediately after the event and two months later. Furthermore, the NDVI was calculated in a period of two years (2017 and 2018) to compare the different situations into the burned areas, considering the vegetation seasonality (e.g. August 2017 vs August 2018, etc.). The resulting rasters were further clipped based on the area identified by RBR and intersected with the land cover map 'Map of Nature of Parco Nazionale Gran Sasso and Monti della Laga' (Bagnaia et al. 2015) (Figure 3).

The NDVI was discretized into 10 classes with values ranging from 0 (0.0 to 0.1) to 10 (0.9 to 1.0), with 10 rep-

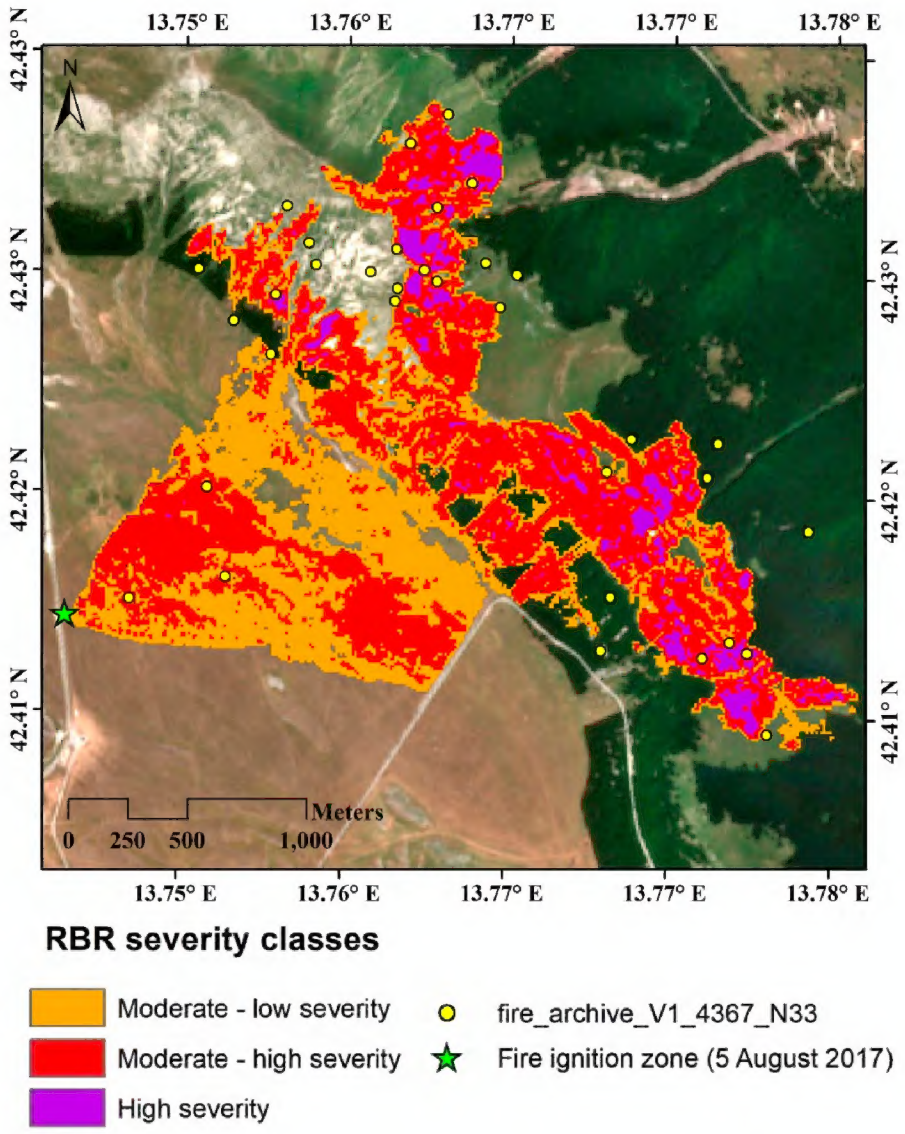

Figure 2. Relativized Burn Ratio (RBR) for the study area. The index has been discretized in three 'burn severity' classes (Moderate-Low, Moderate-High and High severity). The validation points (VIIRS) are marked in yellow, while the point where the 2017 fire was triggered is indicated with green star.

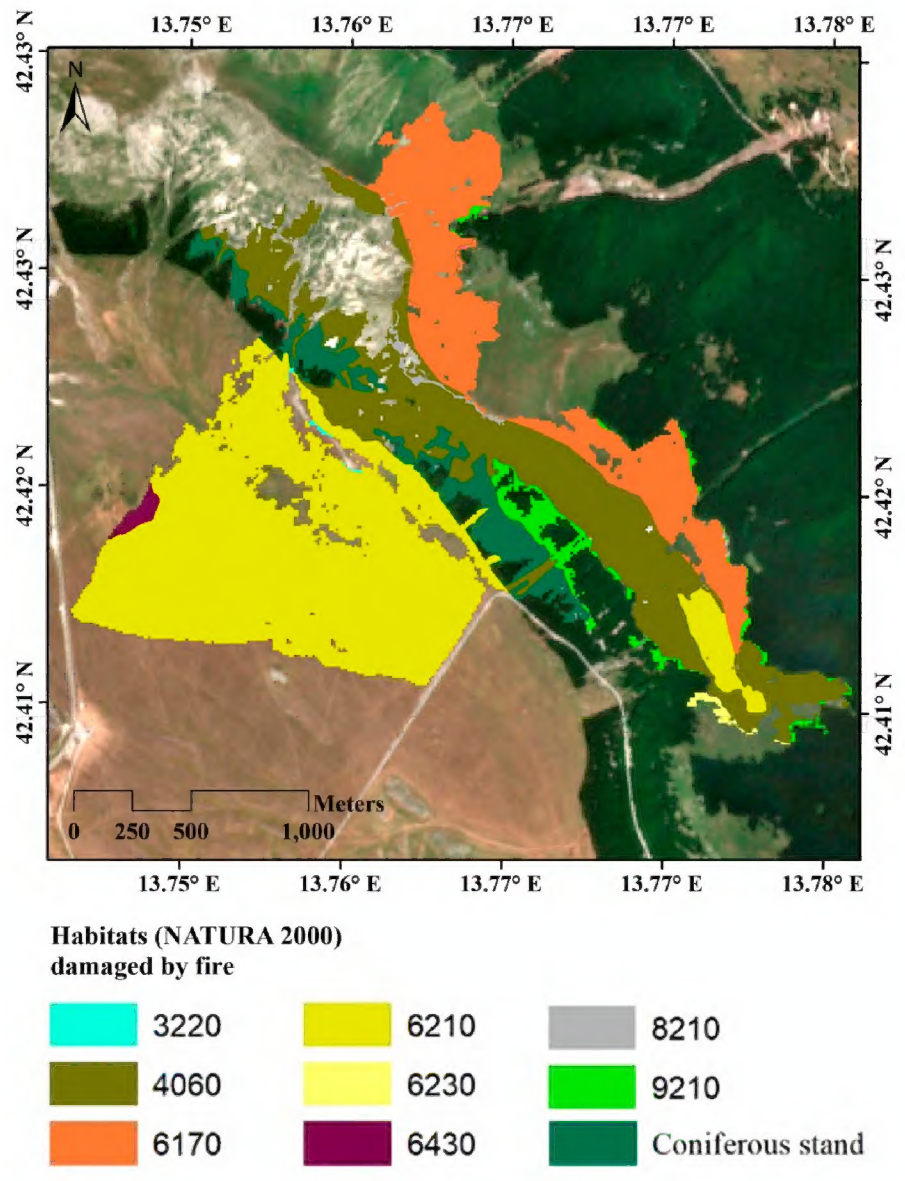

Figure 3. Annex I Habitats burned by the fire of 2017 in the study area. The numerical codes refer to the nomenclature used to identify the Annex I habitats (http://vnr.unipg.it/habitat/, see also Table 1).

resenting the highest photosynthetic activity (Klisch and Atzberger 2016).

Resulting NDVI raster maps were processed through zonal statistics for each type of Annex I habitats affected within each severity class of the RBR (Graser 2016). The seasonality among the years 2017 and 2018 was not considered because of the summer dry period in the study area. Indeed, even considering the wettest season, usually the grasslands became dry at the beginning of July, while for the other vegetation types we could assume that they are not strongly affected by seasonality.

To make the analysis comparable with an undisturbed situation, we built a 500 m buffer around the burned area. The control area ("Unburned control area") was defined based on the presence of the same Annex I habitats identified in the burned area. Furthermore, the buffer was built based on the occurrence of similar topographical conditions. The approach used in this study is shown in the workflow in Figure 4.

Result

Detection of burned area

The area affected by the fire was identified by the Relativized Burn Ratio index. The RF model used to validate the RBR index showed a high degree of classification accuracy with an Overall accuracy of 83% and a Kappa of 77% (Appendix: Table A2). The total area affected by the 2017 fire results in 311.3 hectares. The vegetation types affected by fire can be referred to the followed Annex I habitats: "Alpine rivers and the herbaceous vegetation along their banks" (3220), "Alpine and boreal heaths" (4060), "Alpine and subalpine calcareous grasslands" (6170), "Semi-natural dry grasslands and scrubland facies on calcareous substrates" (6210*), "Species-rich *Nardus* grasslands, on siliceous substrates in mountain areas" (6230*), "Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels" (6430), "Calcareous rocky slopes with chasmophytic vegetation" (8210), "Apennine beech forests with *Taxus* and *Ilex*" (9210*), as well as several hectares of coniferous stands (Table 1). The pre- and post-fire imagery provided rapid, qualitative and quantitative indications of the areas affected by fire. For each habitat within each 'burn severity' class the NDVI zonal statistics are reported (Table 2).

The habitats more threatened by the wildfire resulted to be the grasslands at low altitude (~1,500 meters) covering 45.2% of the total area, the shrublands at medium altitude (~1,600 meters, 25.08%), the grasslands at high altitude (>1,700 meters, 18.78%), the coniferous stands (6.76%) and the beech forests (2.62%).

Vegetation monitoring

A strong trend resulted from the multi-temporal analysis of NDVI, above all in the grasslands vegetation.

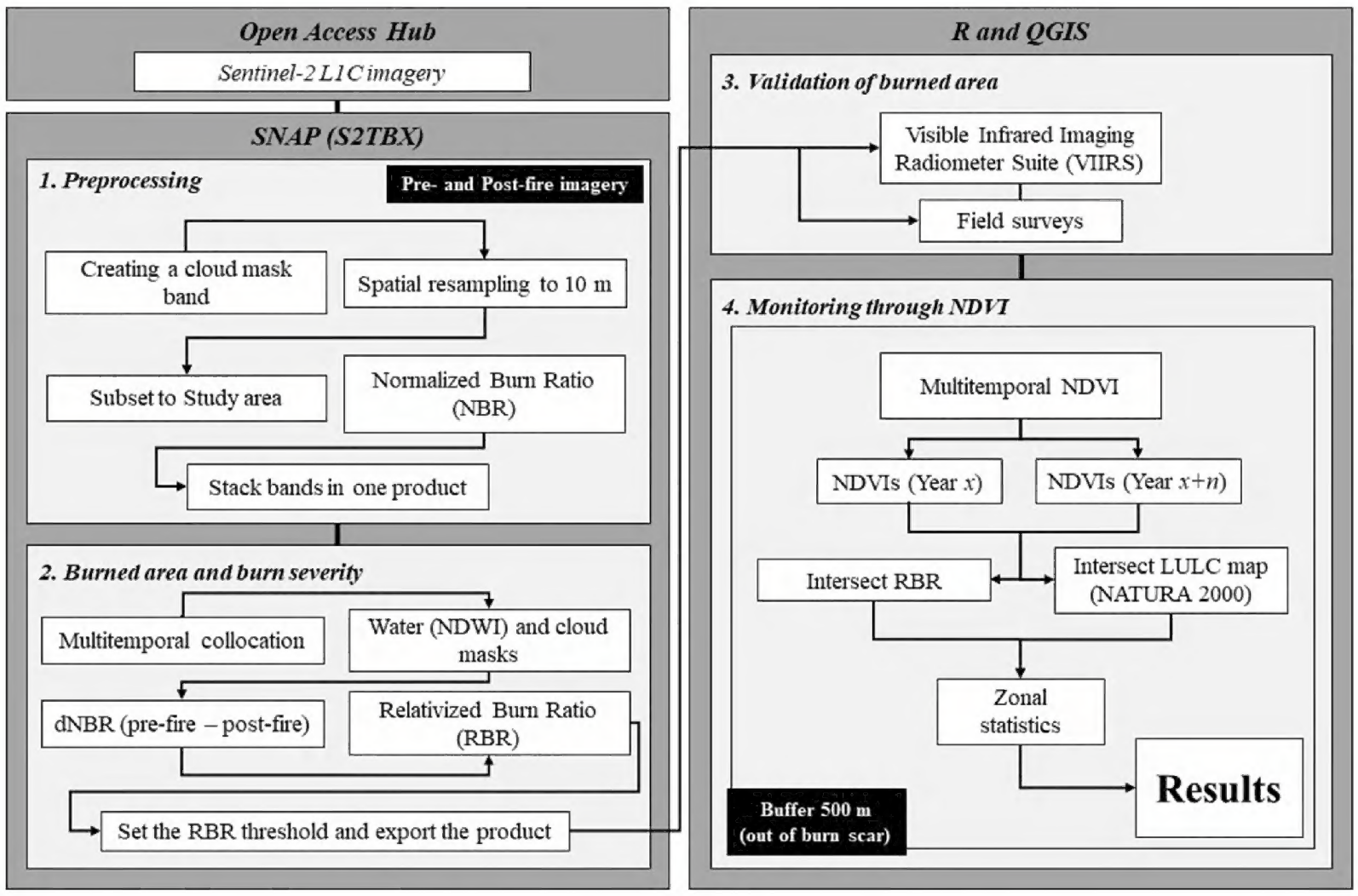

Figure 4. Simplified workflow. Scheme of the procedure for the identification and monitoring of the areas burned by S2 data.

Table 1. EU Annex I codes of the habitat types present in the study area, with relative description (with asterisk the priority habitats; European Commission 2013.

HABITAT CODE	DESCRIPTION
3220	Alpine rivers and the herbaceous vegetation along their banks
4060	Alpine and Boreal heaths
6170	Alpine and subalpine calcareous grasslands
6210*	Semi-natural dry grasslands and scrubland facies on calcareous substrates (Festuco-Brometalia) (*important orchid sites)
6230*	Species-rich *Nardus* grasslands, on siliceous substrates in mountain areas and submountain areas, in Continental Europe
6430	Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels
8210	Calcareous rocky slopes with chasmophytic vegetation
9210*	Apennine beech forests with *Taxus* and *Ilex*

The month of July 2017 (pre-fire) was taken as reference for a 'no disturbed area'. The NDVI values resulted in an average of 6.65 for the grasslands (habitats 6170, 6210* and 6230*), 7.75 for the forests (habitat 9210* and Coniferous stands), and 6.35 for the shrublands (habitat 4060).

In the months following the fire event, the NDVI values were in clear decline, especially immediately after the event (August 2017), showing average values of 3.50 for the grasslands, 4.23 for the forests, and 2.88 for the shrublands.

Interestingly, in October 2017, only two months after the event, an increase in NDVI values was observed. In particular, the grasslands showed high average values (NDVI = 5.10), unlike the shrubland and forest habitats.

The monitoring for the year 2018 showed other interesting values. In particular, the grasslands at low and high elevation (habitats 6170*, 6210*, 6230*, 6430) revealed an average value of NDVI = 7.27 for the month of July, and ~ 6.50 for the months of August and October.

In the same year, the forest habitat and the conifer stands also showed increasing values. All these trends are shown in Figure 5 and in Table 2.

The NDVI values (Table 2) within the three 'burn severity' classes show a very similar trend in the Moderate-Low and Moderate-High severity classes, that occupy respectively 42.24% and 51.03% of the total area. Instead, the High severity class (6.72% of the total burn scar) reveals a more resilient response to the extreme event with values that rise more rapidly towards stability. The com-

Table 2. Zonal statistics for each Annex I habitat affected by fire within each severity class of the RBR (Relativized Burn Ratio). The NDVI values was discretized into 10 classes with values ranging from 0 (0.0 to 0.1) to 10 (0.9 to 1), with 10 representing the highest photosynthetic activity. The numerical codes of the habitats correspond to: Alpine rivers and the herbaceous vegetation along their banks (3220), Alpine and Boreal heaths (4060), Alpine and subalpine calcareous grasslands (6170), Semi-natural dry grasslands and scrubland facies on calcareous substrates (*Festuco-Brometalia*) (*important orchid sites) (6210*), Species-rich *Nardus* grasslands, on siliceous substrates in mountain areas and submountain areas, in Continental Europe (6230*), Hydrophilous tall herb fringe commu-nities of plains and of the montane to alpine levels (6430), Calcareous rocky slopes with chasmophytic vegetation (8210), Apennine beech forests with *Taxus* and *Ilex* (9210*).

	NDVI AVERAGE VALUES WITHIN HABITAT NATURA 2000									
BURN SEVERITY CLASS (RBR)	3220	4060	6170	6210	6230	6430	8210	9210	Coniferous stands	Total
Moderate-low severity [1]	5.20	5.95	6.98	5.32	7.82	5.06	4.97	8.27	7.16	6.42
Moderate-high severity [2]	5.00	6.54	6.90	5.16	7.44	5.29	6.09	7.89	7.42	6.57
High severity [3]		7.32	7.39	6.06	7.50		6.67	8.00	8.86	7.40
Total Burned	5.19	6.35	7.01	5.26	7.67	5.12	5.39	8.16	7.33	6.55
Total Unburned (buffer 500m)	4.00	5.30	6.61	5.23	7.06	5.10	4.38	7.90	7.56	6.17

JULY 2017

	NDVI AVERAGE VALUES WITHIN HABITAT NATURA 2000									
BURN SEVERITY CLASS (RBR)	3220	4060	6170	6210	6230	6430	8210	9210	Coniferous stands	Total
Moderate-low severity [1]	3.38	3.38	4.16	3.42	4.27	3.40	2.85	4.66	4.62	3.87
Moderate-high severity [2]	3.00	2.64	3.07	3.24	3.23	3.18	2.40	3.56	3.56	3.05
High severity [3]		1.75	2.09	1.69	2.00		1.50	1.50	3.21	2.00
Total Burned	3.33	2.88	3.40	3.32	3.77	3.32	2.69	4.31	4.15	3.39
Total Unburned (buffer 500m)	3.17	4.97	6.09	4.34	6.52	3.20	4.36	7.63	7.02	6.16

AUGUST 2017

	NDVI AVERAGE VALUES WITHIN HABITAT NATURA 2000									
BURN SEVERITY CLASS (RBR)	3220	4060	6170	6210	6230	6430	8210	9210	Coniferous stands	Total
Moderate-low severity [1]	4.46	3.69	5.14	5.66	5.12	6.85	3.22	4.47	4.79	4.62
Moderate-high severity [2]	5.00	3.34	4.63	5.45	4.69	6.83	2.91	3.94	3.58	4.11
High severity [3]		3.53	4.19	4.00	5.00		3.50	4.75	3.43	3.84
Total Burned	4.48	3.52	4.77	5.55	4.98	6.85	3.12	4.33	4.26	4.34
Total Unburned (buffer 500m)	4.09	4.90	6.03	5.27	5.74	5.06	4.57	6.59	7.12	5.85

OCTOBER 2017

	NDVI AVERAGE VALUES WITHIN HABITAT NATURA 2000									
BURN SEVERITY CLASS (RBR)	3220	4060	6170	6210	6230	6430	8210	9210	Coniferous stands	Total
Moderate-low severity [1]	6.17	5.05	7.15	7.38	7.69	7.60	4.04	6.16	5.21	5.98
Moderate-high severity [2]	6.00	5.10	6.20	7.34	7.54	7.50	3.84	5.50	4.55	5.67
High severity [3]		5.73	6.20	7.18	8.50		4.00	6.50	3.80	5.96
Total Burned	6.15	5.16	6.50	7.35	7.65	7.57	3.97	5.99	4.86	5.84
Total Unburned (buffer 500m)	5.67	5.78	7.37	6.86	7.48	6.18	5.08	8.24	6.54	6.71

JULY 2018

	NDVI AVERAGE VALUES WITHIN HABITAT NATURA 2000									
BURN SEVERITY CLASS (RBR)	3220	4060	6170	6210	6230	6430	8210	9210	Coniferous stands	Total
Moderate-low severity [1]	5.70	5.14	6.85	6.48	7.30	5.81	4.37	6.17	5.28	5.80
Moderate-high severity [2]	6.00	5.12	6.00	6.54	6.94	5.38	4.31	5.56	4.84	5.52
High severity [3]		5.94	6.26	6.86	8.00		5.00	6.75	4.47	6.05
Total Burned	5.75	5.23	6.36	6.52	7.19	5.67	4.36	6.02	5.06	5.70
Total Unburned (buffer 500m)	5.56	5.60	6.77	6.07	7.00	5.32	5.14	6.96	6.46	6.06

AUGUST 2018

	NDVI AVERAGE VALUES WITHIN HABITAT NATURA 2000									
BURN SEVERITY CLASS (RBR)	3220	4060	6170	6210	6230	6430	8210	9210	Coniferous stands	Total
Moderate-low severity [1]	5.48	5.06	6.67	6.54	6.86	6.33	4.28	6.45	5.49	5.80
Moderate-high severity [2]	6.50	5.08	5.85	6.52	6.82	6.17	4.28	5.85	5.03	5.48
High severity [3]		5.86	6.13	6.67	8.00		4.33	6.25	4.76	5.95
Total Burned	5.57	5.16	6.22	6.54	6.87	6.29	4.28	6.28	5.27	5.67
Total Unburned (buffer 500m)	5.22	5.53	6.71	6.15	7.13	5.75	4.94	8.61	6.85	6.55

OCTOBER 2018

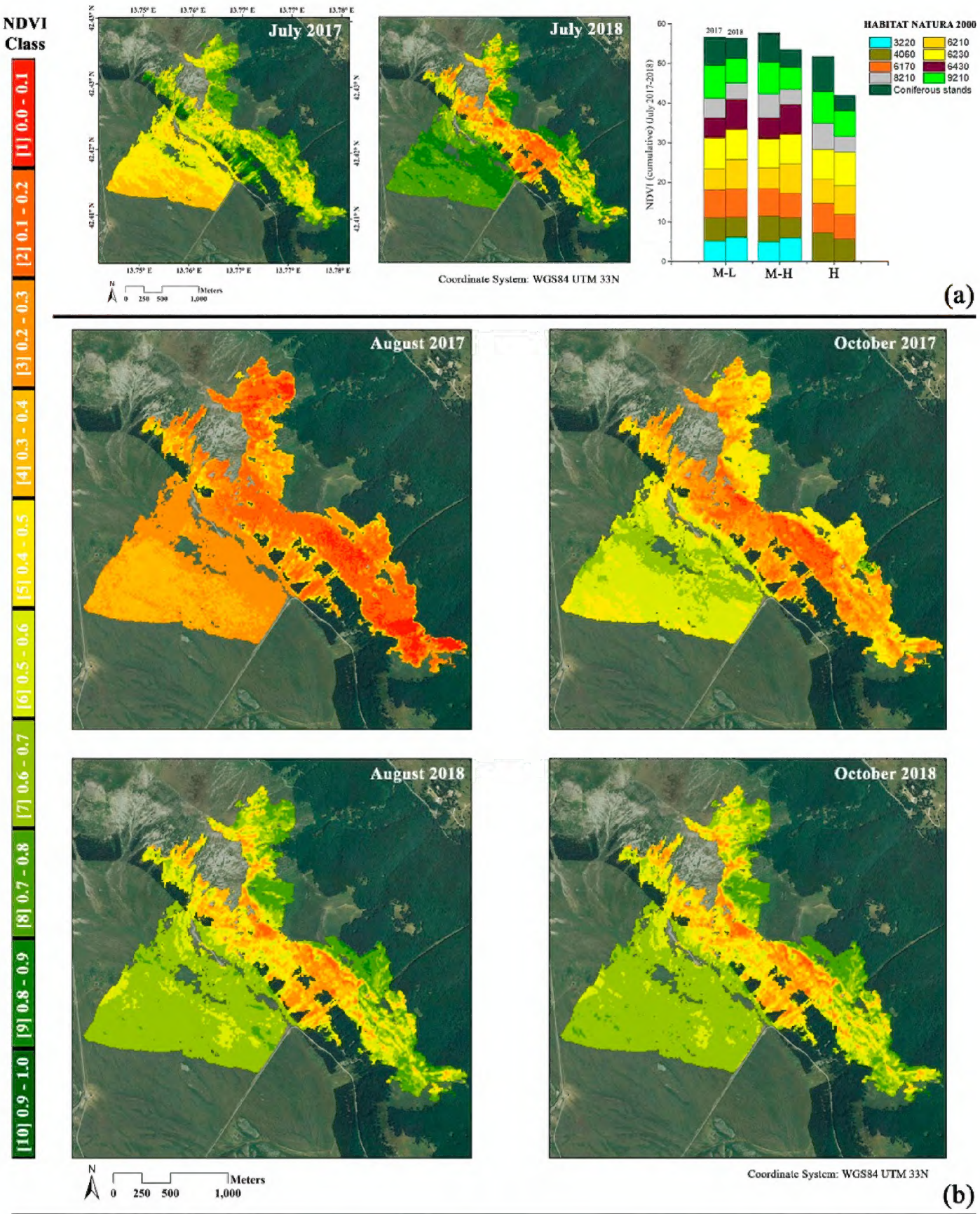

Figure 5. NDVI trends in the burned area and cumulative areas shared by habitats threatened by fire. (a) Monthly comparison in two years of monitoring (July 2017 and July 2018). (b) Comparison of NDVI discrete maps for the monitored months (August 2017, October 2017, August 2018 and October 2018). (c) NDVI average trends in all the monitored months, within the 'burn severity' classes (M-L= Moderate-Low severity; M-H = Moderate-High severity; H = High severity). The different colors of the cumulative columns represent the Annex I habitats threatened by fire in the study area.

parison between the Unburned control area and the Total burned area resulted in a clear trend: 1) all plant communities followed their normal phenological cycle in the area not affected by the fire, shoving similar NDVI values over time; 2) in the burned area, a decrease of NDVI values can be observed after the fire event; the index rises again in the following months, although it never reaches the original values again. All these trends, including those of the most damaged habitats mentioned above, are shown in Figure 6.

Discussion

Fire is an important disturbance process in many ecosystems, e.g. Mediterranean ecosystems (Keeley et al. 2011), but its intensity and frequency are altered by humans in many areas as a result of land use change (Bucini and Lambin 2002) or, as in the present study, of an accidental fire. Multispectral sensors have been used to monitor active fire, map burned area, or quantify fuel availability and flammability (Herawati et al. 2015).

The study area was well suited for testing the potentiality of the S2 data to obtain the specific spectral indices used for vegetation monitoring (RBR and NDVI). Moreover, it allowed the investigation of the short-term dynamics of vegetation recovery, even verifying in the field the satellite-collected data (pers. obs.).

This study identified and characterized the burned areas at medium-high resolution, taking advantage of the spectral and temporal characteristics of the MSI S2 data. The large temporal resolution of these data (5 days) allowed a very precise use of the RBR index, as described above, based on pre- and post-fire imagery. This index, calculated at the spatial resolutions we used, allowed the identification of burn scars with great rigor. It also enabled us to discretize the burned area into severity classes and allowed to carry out both an exploratory analysis of the most affected areas and a more thorough investigation using the NDVI.

The analysis conducted within the 'severity classes' using the NDVI showed a clear pattern of similarity of the less severe ones, which showed relatively regular trends in values. On the other hand, a faster increase was found in

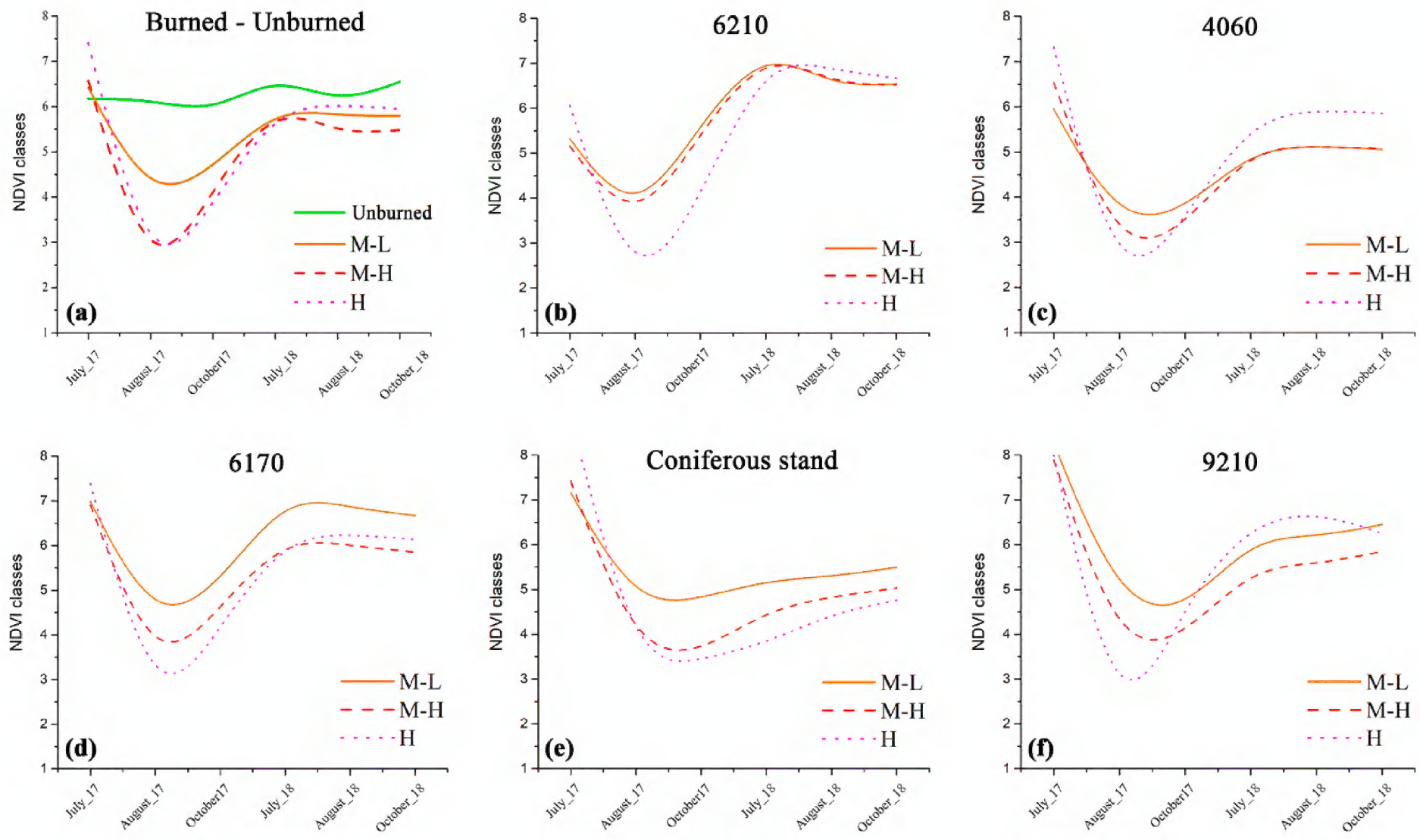

Figure 6. NDVI trends of the total burned and unburned area, and within 'burn severity' classes, in the threatened habitats. 'Burn severity' classes: M-L = Moderate-Low Severity (orange solid line); M-H = Moderate-High Severity (red dash line); H = High Severity (violet dotted line). (a) NDVI average trends of unburned areas in a 500 meters buffer around the burned scar (green solid line), and 'burn severity' classes (M-L, M-H, H) for the total threatened area. The other graphs represent the NDVI average trends within the 'burn severity' classes for different Annex I habitats plus coniferous stands: (b) 6210* (Semi-natural dry grasslands and scrubland facies on calcareous substrates), (c) 4060 (Alpine and boreal heaths), (d) 6170 (Alpine and subalpine calcareous grasslands), (e) coniferous stands, (f) 9210* (Apennine beech forests with *Taxus* and *Ilex*). The habitats 6230* [Species-rich *Nardus* grasslands, on siliceous substrates in mountain areas (and sub-mountain areas, in Continental Europe)], 6430 (Hydrophilous tall herb fringe communities of plains and of the montane to alpine levels) and 8210 (Calcareous rocky slopes with chasmophytic vegetation) are not included because of the limited extent of their patches.

the higher class, confirming a greater resilience at highly burned sites (Coop et al. 2016).

Results show that the most affected habitats are the grasslands (6170, 6210, 6230, 6430) and shrublands (4060). As far as the former are concerned, the analysis lead to interesting results, showing how the herbaceous vegetation, even in montane and sub-alpine environments, can rapidly recover, similarly to the Mediterranean communities. This might also (partly) be due to a rapid vegetation recovery in the first two years after the fire, becoming more gradual in the following years (Petropoulos et al. 2014).

However, extreme events, such as fires, can have very important effects on the structure and composition of grasslands (Venn et al. 2016). In the study area, a collapse of the vegetation cover just after the event was observed, followed by a recovery that favored the abundance of graminoids species with a large seed bank, as reported by Buma (2012).

Shrublands were damaged for a quarter of the total area. These communities are mainly constituted by common juniper (*Juniperus communis* L.). Our results are in line with Quevedo et al. (2007), who reported less resilient communities with poorer regeneration capacities, a result comparable to ours obtained by NDVI monitoring approach.

The coniferous forests in the study area are characterized by mixed reforestations with European silver fir (*Abies alba* Mill.), European spruce [*Picea abies* (L.) H. Karst.], European larch (*Larix decidua* Mill.) and Austrian pine (*Pinus nigra* J.F.Arnold). They represent less than 10% of the entire study area. The scarcity of active maintenance over the years made these woods very susceptible to fire, given the quantity of combustible material in the undergrowth (Moreira et al. 2009). In addition to their poor regenerative capacity (Catry et al. 2010), in the study area these plantations grow on steep slopes, which probably determines a slower recolonization.

The last habitat affected by the fire of 2017 was the beech forest (9210), representing less than 3% of the burn scar. Beech forests are not very resilient to the passage of the fire, because of the low seed vitality after such events. Interestingly, a positive trend was observed in the NDVI index values, accounting for a good regenerative capacity, due to the development of the herbaceous undergrowth species present in the seed bank. In fact, the fertile soil of beech woods can facilitate the development of herbaceous vegetation (and therefore an increase in its photosynthesis index) in the period following the fire (Ascoli et al. 2013). These species take advantage of better light and moisture conditions (Maringer et al. 2012; Gratani et al. 2018). The increase in NDVI values in burned beech patches may be partly due to the 'edge effect' with the nearby beech forest not affected by fire. This effect was not considered in our study, but it appears to be the least significant with respect to the surface coverage of the vegetation (competition) and the mature trees which survived the post-fire (seed sources), followed for importance by topographical factors (Fang et al. 2019). The high values of NDVI in wooded areas could also be due to errors in the index, which saturates when dealing with high density of vegetation; furthermore, its application is hindered in dense and structurally complex vegetation complexes (Quang et al. 2019). Despite the aforementioned disadvantages, the NDVI was here used because the affected forest area, compared to the other habitat types, covered little extent.

Satellite remotely sensed data and analyses have been widely applied in both conservation science and practice, but there are limitations to the information they can provide. In this study, the spatial resolution of S2 sensors allowed the identification of short-term trends in the photosynthetic activity of the different plant communities after the fire event, and a very accurate study of the vegetational dynamics in progress. On the other hand, in order to obtain more accurate information regarding individual populations or single species, there is a need for satellite data with a very high spatial resolution (VHR, usually commercial) that have a relatively high cost, depending on the purpose and the request (Marvin et al. 2016).

The field sampling effort for monitoring an area of this size requires considerable monetary and human resources. The use of SRS not only reduces the field work but also facilitates possible actions to restore the area interested (Dey et al. 2018). Furthermore, the use of ancillary data obtained through 'crowdsourcing' (Citizen science) might facilitate and/or further reduce field surveys by allowing analysis at ever larger and more accurate scales (Hufkens et al. 2019).

The use of satellite remote sensing for vegetation monitoring has allowed to observe the situation from a different perspective, compared to the classic field surveys. Through this methodology, it was possible to carry out a high resolution multitemporal analysis.

This study provided a rapid and effective monitoring of the conditions of various plant communities, including a quantification of damage and tendency to short-term recover. Furthermore, with the applied methodology it was possible to detect and quantify different burn severity classes, allowing an even more extensive study of the vegetation recovery dynamics. This approach can also make field work more efficient by focusing sampling efforts on certain areas, in order to implement specific environmental recovery measures for damaged habitats at a relatively low cost.

The proposed approach provides useful management information for fire prevention in protected areas, planning monitoring activities and implementing functional rehabilitation actions for habitats affected by these disturbing events.

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Appendix

Table A1. Satellite images used for the analysis.

Satellite Instrument	Acquisition date	Product types	Pre/Post Fire
Sentinel-2 MSI	20.07.2017	Level-1C	PRE
Sentinel-2 MSI	29.08.2017	Level-1C	POST
Sentinel-2 MSI	28.10.2017	Level-1C	POST
Sentinel-2 MSI	10.07.2018	Level-1C	POST
Sentinel-2 MSI	29.08.2018	Level-1C	POST
Sentinel-2 MSI	13.10.2018	Level-1C	POST
Planet Scope MSI	10.08.2017	Level 1B	POST

Table A2. Accuracy statistics. Classification accuracy (%) for the index classification when applied to the validation dataset. Training data consisted of a random sample (80%) of the full dataset and validation was conducted on the remaining data.

Overall Statistics				
	Accuracy: 0.8333		**Kappa**: 0.7778	
	95% CI: (0.3588, 0.9958)		**P-Value [Acc > NIR]**: 0.01783	
	No Information Rate: 0.3333			
Statistics by Class:				
	Class: 1	**Class: 2**	**Class: 3**	**Class: 4**
Sensitivity	0.5000	10.000	10.000	10.000
Specificity	10.000	10.000	10.000	0.8000
Pos Pred Value	10.000	10.000	10.000	0.5000
Neg Pred Value	0.8000	10.000	10.000	10.000
Prevalence	0.3333	0.3333	0.1667	0.1667
Detection Rate	0.1667	0.3333	0.1667	0.1667
Detection Prevalence	0.1667	0.3333	0.1667	0.3333
Balanced Accuracy	0.7500	10.000	10.000	0.9000